Heat-treated wood and its development in Europe

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Abstract: Efficient use of timber is a vital concern problem, especially in these regions where the forestry coverage ratio is decreasing. Studies on physical modification of wood have been taken more attention due to the increasing attentions on environmental protection. Thermal modification is emphasized and developed quickly in developing countries, especially in European countries. A large number of researches have been conducted and some industrial production plants have been built. This paper reviewed the history of heat treatment, exemplifies the industrial developments in several European countries, summarized the basic principle of heat treatment and describes the environmental characteristics. The properties of heat-treated wood and its usage are also summed up.

Keywords: Heat-treated wood; Durability; Dimension stability; Mechanical characteristics; Industrial production
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Introduction

Wood is a kind of natural materials. Due to its poor dimension stability and low durability under variable atmosphere circumstance, researches on stabilization treatment are carried out to limit the moisture absorption by destroying or combining the hydroxyl groups of the wood.

Heat treatment research initiated at the early 20th century. The earliest articles about wood heat treatment were found in 1920s. Stamm and Hansen (1937) researched the swelling and shrinkage of heat-treated wood. Data showed that the hygroscopicity of drying timber fell down considerably but not for wet timber. There was more strength loss for heat-treated wood treated in the air than that in the shielding gas. Stamm *et al.* (1946) reported on the first systematic attempt to increase resistance to wood decayed fungi in a hot metal bath. The report indicated that the improved durability and dimension stability were companied with the loss of strength. When the Anti-swelling shrinkage efficiency (ASE) went up to 40%, the static bending strength decreased by 20%. Buro (1954, 1955) studied the timber treating methods in different shielding gases and in molten baths and found that it had better durability and dimension stability for heat-treated wood treated in metal baths than in shielding gases, but opposite to strength.

In subsequent years, researches on heat-treated wood were pursued by wood scientists in different countries. The interests often focused on drying properties, chemical changes of wood components (Troya *et al.* 1994; Tjeerdsma *et al.* 1998), increased dimension stability (Stamm *et al.* 1946; Seborg *et al.* 1953), improved durability (Dirol *et al.* 1993; Jämsä *et al.* 1998; Kamdem *et al.* 1999) and physico-mechanical properties (Viitanen *et al.* 1994; Byeon HeeSeop *et al.* 1996). Burmester (1972) found improved properties of wood on which thermal pressure was applied. This process was further developed by Giebeler (1983). He researched the dimension stability by treating the wet timber of different species with heat and pressure. The results indicated that the swelling rate fell by 50%-80% for these species, such as beech, birch, pine, poplar, and spruce, which were treated at the temperature of 180-200 °C. Hillis (1984) found that strong effects occurred on the plasticized hemicellulose and lignin when timber was treated at temperature of 100 °C for 2 h. Bourgois and Guyonnet (1998) reported the thermal degradation of wood treated with high temperature and speculated on the principle of property changes for heat-treated wood. D-Yakonov-KV (1990, Russia) treated *Pinus sylvestris* and *Betula alba* at temperature of 80 °C, 100 °C, 115 °C, 130 °C, and 140 °C for 48 h and 96 h, then observed the relationship between hygroscopicty and surface ablation after aging. The lower hygroscopicity was obtained in higher treating temperature and longer treating time, and surface ablation magnified and hygroscopicity dropped with the development of aging.

Dirol and Guyonnet (1993) treated timber by Retification process to improve its durability; that is to say, the timber was treated under the temperature of 200-260 °C for short time without air. Retified wood was defined as a material based on natural wood that has been retified, i.e. that has undergone chemical bonding at macromolecular level. The treated timber by Retification process could get good durability. Viitaniemi and Jämsä carried out the research of heat-treated wood for application in 1995. Viitaniemi published documents to discuss the durability improvement and other properties of heat-treated wood (Viitaniemi 1997, 1998). Cao Jinzhen and Zhao Guangjie (1997) investigated the thermo-dynamic course of water adsorption of

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heat-treated wood. The experiments surveyed the isotherm of water adsorption at temperature of 20 °C and 50 °C for the untreated control and the treated spruce at temperature of 150 °C, 180 °C and 230 °C, respectively. The differential heat of water adsorption, changes of free energy and entropy, and the relationship between wood moisture content and treated temperature were also investigated. The results revealed that the mechanism of water adsorption of heat-treated wood had changed. It was different from untreated control. With the rising temperature, hemicelluloses, which have strong ability of water adsorption, degraded to give birth to furfural, etc.. So the hygroscopicity dropped. The differential heat of adsorption and entropy declined with the rising of treating temperature. The reason was that the amount of hydrogen bonding was declined between H_2O and wood molecules. Boonstra *et al.* (1998) carried out the thermal modification for the non-durable wood and developed Plato technology and Tjeerdsma expatiated the properties of Plato wood.

Further investigations and studies are carried out in the late 20th century. Sundqvist, B. *et al.* (1999, Sweden) probed the color changes of drying timbers in the industrial kiln at the temperature of 70 °C and 100 °C. Data indicated that the color changes occurred mainly on the capillary phrase above Fiber Saturation Point. The color changes under Ultraviolet were investigated for the heat-treated sapwood and heartwood of *Betula pubescens*, *Picea abies*, *Pinus sylvestris.* The results showed that, compared with their respective untreated control, the treated *Picea abies* and *Pinus sylvestris* had severer color changes than treated *Betula pubescens.* Higher treating temperature and longer treating time are, more color changes to heat-treated wood. Kubojima, Y. *et al.* (2000, Japan) studied the bending strength and rigidity of heat-treated spruce that was treated at 160 °C for 0.5-16 h in nitrogen or air. The bending strength and impacting toughness rose at the initial stages and then dropped. Heat-treated wood treated in the air had more loss on bending strength and impacting toughness than that treated in the nitrogen. With the longer treating time, heat-treated wood showed lower destructive work in the nitrogen than that in the air. This made clear that viscosity and plasticity, not elasticity, caused the drop in the destructive work although heat-treated wood was more brittle than untreated control. Risto, A. Kotilainen *et al.* in 2000 developed a multivariate chemometric method for monitoring the mass loss of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). Chemical changes during the heat treatment (160-260 °C for 2-8 h) of wood were determined by IR spectroscopy. This method seemed to have a potential for rapidly and accurately determining the mass loss of wood feedstock during heat treatment at temperatures of 160-260 °C.

The attempts to improve wood characteristics have been continuing in these years. Many literatures spring in the journals and websites. At the same time, the various wood improvement processes were documented in patent specifications (e.g. US-5678324; EP-0759137). The quality control system is focused on in many plants. The uniform standard for scaling the properties of heat-treated timber should be developed urgently in next work.

Currently commercialized heat-treated wood

Although research was conducted early, heat-treated wood has not been commercialized until recently years. The reason is mainly that the processes are complicated in large-scale production due to high temperature. Another problem is wood's burning if shielding gas isn't used. The treatment decreases wood's strength and makes it too brittle for many applications.

With the development of technology and economy in these years, recent efforts have led to development of heat treatment of wood. The processing technology developed quickly. The improvements in these products to dimension stability and durability were obvious. Several modified products are previously or presently introduced to the market, mainly in European market. These commercialized products are mainly developed in Netherlands, Germany, France and Finland.

Heat-treated wood in Netherlands

In the summer of 2000, PLATO-wood was developed in the Netherlands (Holger *et al.* 2000). A production plant was built and started its production. This plant was initially designed to treat 50 000 m³ wood. PLATO process combined the wet-thermal treatment and dry-thermal treatment in routine seasoning. Chemical changes occurred among wood components in the wet-thermal treatment. The process in the wet-thermal condition was expected to enhance the cell wall reactive activity of wood components at relatively low temperature. In order to decrease the negative effects and get the satisfactory products, the soft treating parameters were taken to control the degradation of hemicellulose (Tjeerdsma *et al.* 1998). The PLATO process principally had three treating steps. On first step the green or air-dried timber was treated at typical 160-190 °C for 4-5 h under some pressure. The second step was in routine seasoning. On this step the treated timber was dried to about 10% moisture content for 3-5d. The third step followed was that the dried timber was heated at temperatures of 170-190 °C for 14—16 h. After the treatment, the products were stored and conditioned for 2-3d. The shielding gas was water steam or hot air. The treating time depended on end usage, wood species used, the thickness and form of timber. The PLATO-wood production costs about 100 Euro per cubic meter. The costs included handling costs, energy, water, depreciation of the plant, etc., excluding the costs of timber itself. The sale price depended on timber species and end usages. The operating costs were 20 Euro/m³, including water, energy, disposal of sewage, etc.. The plant construction cost was 10 to 15 million Euro for a plant with of annual capacity of 75 000 m³.

The properties of PLATO-wood were analyzed. The re-

sistance against all of fungi used in analysis was improved considerably after treatment, especially efficient against brown rot fungi. The average strength loss from 5% to 18% was found for PLATO-wood. It was much less than 50% or more in earlier studies. Some defects (mainly cracks) could occur during the process since plank was exposed to high temperatures and had rapid water evaporation. Some of the wood species, specially several softwoods known to have a high resistance against liquid impregnation, were difficult to be treated due to occurrence of defects. Treating temperature and wood species predominantly affected the strength of wood. The hygroscopicity was the most essential characteristics of wood that had a major influence on both dimension stability and durability. The lower hygroscopicity was found due to the changes of components in heat-treated wood. The hysteresis was the typical characteristic. The study showed that heat treatment didn't diminish the hysteresis. Heat treatment made the swell reduce substantially and the swell reduction was found independent of the relative humidity. The results showed that ASE of heat-treated wood could go up to approximately 50%. This was near the maximum reachable ASE under the examined process conditions. ASE in tangential direction was higher than that in radial direction. The decreased difference in ASE between tangential and radial direction caused less tensions in heat-treated wood when exposed to changeable climatic conditions.

Heat-treated wood in Germany

One plant with a capacity of 2 900 $m^3 \cdot a^{-1}$ is current in commercial use in Germany. The plant has been operated since August 2000 by MENZ HOLZ in Reulbach. The scheming future vessel has typical capacity of 8 500 $m^3 \cdot a^{-1}$. The plant chose some oils as treating media, which had higher boiling points than required treating temperature. Better improvements were expected with oil compared to air. Fig.1 showed the principal design of its plant.

The process was performed in the closed process vessel (Andreas *et al.* 2000). After loading with timber in the process vessel, hot oil was pumped from the stock vessel into the process vessel where the hot oil was kept circulating around the wood at high temperatures. Before unloading the hot oil was pumped back into stock vessel. Concerned about the environment protection, the nature plant oils were chosen. The chosen oil must have higher boiling point temperature than the treating temperature. Due to the volatilization of oil, the oil would become thick. The component and color would also change because of the mixture with the degradable wood components. Here more concerns were not only about fast and uniform heat conduction and oxygen isolation but also about oil smoking point and tendency of polymerization. Therefore good oils must be chosen according to the end usage. For different end usage, different treating temperature and time were used. In order to achieve the maximum durability and the expected oil load, the timbers were treated at around 220 °C and cooled off in the oil bath for some time. In order to get the best durability and maximum strength, the timbers were treated at 180-220 °C. The total treating time for a 4-meter length, 100-mm-diameter log, including heating and cooling time, was 18h.

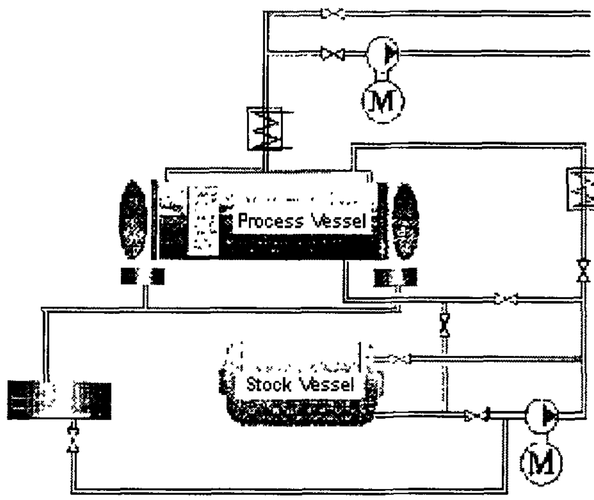

Fig. 1 Principle design of the plant (Courtesy of MENZ HOLZ in Germany)

Investment for a capacity of 8 500 $m^3 \cdot a^{-1}$ was about 450 thousand Euros. Based on 10-year use life, the depreciation costs were 5.2 Euro/m³. Operation costs for treatment of spruce were from 60 Euro/m³ to 90 Euro/m³, depending on the desired oil load. Covering other possibilities, the costs of oil-heat treated spruce were 265-295 Euro/m³ based on costs of untreated timber of 200 Euro/m³.

Due to the behavior of plant oils in conjunction with effect of heat, improvement could be expected on various wood characteristics from the application of hot oil compared to gaseous atmosphere. The biological durability was measured by incubating specimens into a Kolle flask for 19 weeks. The percentage loss of mass was determined by comparing the mass before and after incubation. The results showed loss of mass was 40%-50% for untreated control, but average loss of mass for heat-treated wood was 5%-11%. There was no obvious reduction in the value of MOE. The MOR decreased by 20%-30% or so. The impacting strength declined by 50% or even more. So wood became brittle. Due to the additional water-repellent effect of the oil component, the timber treated with hot oil proved to have less hygroscopicity and better dimension stability in open area.

Heat-treated wood in France

Due to changeable atmosphere, some wood species showed low dimension stability and durability, which prompted the development of wood stabilitation for decreasing the hygroscopicity of fiber materials. In recent twenty years, a method was to treat timber at 180-250 °C depending on different species and required strength. The important end aim was to reduce the hygroscopicity by

degradation to reconstruct chemical structures in wood components with the shielding gas and heat. During the treatment, it was found that the parameters affected the end properties of products. The treating condition was very important. Treating temperature, treating time, species, timber moisture content, timber density and dimension should be concerned due to their strong effects on heat-treated wood properties. A balance was found between the improvement of resistance to hygroscopicity and reduction of strength.

In France two main processes are used at the present time. The first one called Retification (Retified Wood) has been developed by Ecole des Mines de Saint-Etiemme. Operating licenses and patents have been acquired by the company-NOW (New Option Wood), (Also known as RETITECH), (Bourgois *et al.* 1998). In this process timber with about 12% moisture content was heated up to 210-240 °C in a vessel with nitrogen as shielding gas. The concentration of oxygen was no more than 2%. Company Four et Brûleurs REY developed the industrial vessel. Three units were in operation with a capacity of 3 500 $m^3 \cdot a^{-1}$ corresponding to each heat vessel of 8 m^3. New order has been put into practice in April 2001 and the production of heat-treated wood has been enlarged two times. The other process was named "Le Bois Perdure" and its process units were developed by BCI-MBS. In this process green wood was allowed to be used. The first step was to dry the green wood in the vessel slightly and at the temperature of 230 °C under steam atmosphere (steam generated from the water of the timber). Eight units are already in operation for this process. Totally industrial production in France was about 8 000 $m^3 \cdot a^{-1}$ at present.

Compared with two processes above, the similarity is that higher treating temperature causes better durability but lower strength. The durability is excellent for heat-treated wood at 230-240 °C, but severe loss of MOR (40%) and brittleness is found. The brittleness and strength of some heat-treated wood species treated at 210 °C are similar to that of untreated control, but little improvement on durability. This means the process parameters should be adjusted depending on different end usages. The properties of wood are sensitive to treating temperature during the process. Little changes of temperature would probably have obvious effect on properties. So the accurate control of temperature should be emphasized. For example, during the process of Retification wood, 230 °C was the temperature to intercross for lignin. So the temperature should be higher than 230 °C in order to get better durability.

For the Retification process, the total investment for an annual capacity of 3 500 m^3 is in the range of 750 000 Euro, but for "Le Bois Perdure" process seems to be less 500 000 Euro. Different processes cause different product cost. Sometimes the treating cost of byproducts should be added. Generally, the cost of Retification process is 150-160 Euro/m^3 and 100 Euro/m^3 for "Le Bois Perdure". However, the yield of the Retification process is more than that of "Le Bois Perdure" due to easier control.

Strength properties are dependent on the parameters of the process, but, in any case, the treated timber became more brittle. At 230 °C, MOR loss can reach 30%-40%. For paintings and finishings usually used to untreated timber, they aren't suitable to be used to heat-treated wood. New formulations of painting and finishing should be developed. The hygroscopicity of heat-treated wood keeps at the level 4%-5% in EMC instead of original 10%-12% in EMC. The low hygroscopicity contributes to biological durability. After exposed to sun or UV for a few weeks, heat-treated wood turned gray in color. Such gray color is more homogenous than that of untreated timber exposed at the same conditions.

Heat-treated wood in Finland

In the early 1990s, Finland built its first heat treatment plant. Much research work was carried out at the same time. The first plant was built in Mantta. So far, there are eight plants called traditional heat treatment plants and one quite big plant is under construction in Finland today. The capacity of these eight plants was little and about 50 000 $m^3 \cdot a^{-1}$ and the yield was about 35 000 $m^3 \cdot a^{-1}$. The treatments excluded from chemicals or pressure, only heat and water steam. The treatment was similar to the Chinese high-temperature drying.

Fig. 2 showed the sketch of principal of the heat treatment plant (Tuula *et al.* 2000). In this sketch, heat comes from electric resistance (Some plants used waste materials, such as bark, sawdust and plant dust to produce heat). Fans drive hot air to heat timbers by making it circulate at adequate rate around timber loads. The air rate is about 10 m/s. The bars must be used between timbers to get uniform air circulation. Steam generator produces some water steam to shield timber from burning. The air content must be under 3.5%. Detectors could measure these parameters, such as air temperature, timber temperature and moisture content, then computer records the measured information. The process can be controlled automatically by computer according to these records and instructions. The process has three steps: firstly, the temperature of treating room is quickly arisen to 100-150 °C; secondly, the temperature is driven to required temperature slowly in 48 h and keeps it for the required time, and then slowly decreases in 24 h. In the rising phase, crack and dark color would be found if moisture content of timber is more than 10%. The temperature in the actual heat treatment period ranges from 150 °C to 240 °C and must be kept constant. The actual process time at constant summit temperatures takes from 0.5 h to 4 h. But the total process time during the period of rising temperature and cooling down temperature is about 72 h. In this process, the temperature difference between circulating air and timber should be decreased. The heat-treated wood will lose its properties. Steam affects the qualities of timbers, but also protects timbers from burning.

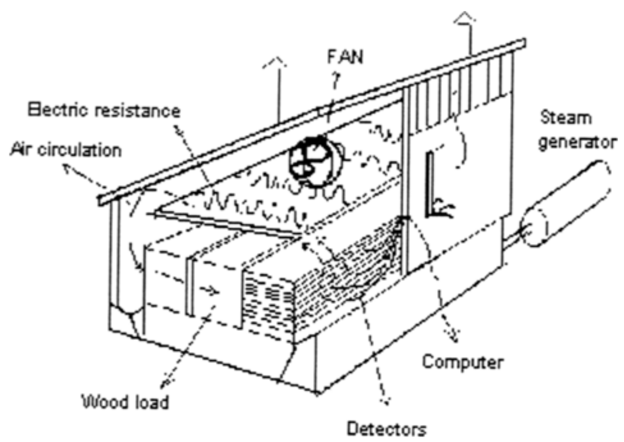

Fig. 2 The sketch of principal of heat-treating plant (Courtesy of Tuula Syrjänen)

Most of wood species used for heat treatment are pine, spruce, birch and European aspen. The process is different for each species and end properties are different due to different chemical components and cellular structures. Usually softwoods are treated heavily and hardwoods are treated lightly. Temperatures over 150 °C will alter the physical and chemical properties of wood permanently. Heat treatment darkens the color of timber. After treatment, the swelling and shrinkage of the wood will reduce and EMC will drop.

A wood brand T°W was developed by VTT and Finnish industry. The process was at temperatures of 180-250 °C with the shielding steam as conducting gas. Severe chemical reaction occurred in the wood when treating temperature was at more than 200 °C, such as degradation of hemicellulose. What the differences of T°W from other treating methods were that no nitrogen and pressure were used. The treating time depended on dimension of treating room, wood load, timber dimension and rate of rising and cooling temperature. During the process period, there must be an adjustment to decrease the possibilities of crack. The temperature in the treating room depended on the temperature difference of timber between inner and outside. The temperature difference between treating room and timber depended on timber dimension. The treated raw materials were green wood or kiln wood. For green wood, fast drying with steam was completely possible if no concern about color changes and resin flow.

Reasons for the property improvements of heat-treated wood

Reasons for improvement of dimension stability

High temperature comes into being the poor hygroscopic components from the chemical reaction of polysaccharide, aldehyde and acid. At the same time the temperature gets rid of the sorptive water and makes the short distance between the molecule chains in non-crystal zone of cellulose. The increasing amount of combination causes more tropistic molecule chains in non-crystal zone of cellulose. It has dimension stability improved.

Reasons for improvement of durability

The reasons for improvement on durability can mainly be focused on two points. On one hand, hygroscopicity of heat-treated wood is obvious lower that of untreated control. The EMC of heat-treated wood is about 4%-6% under the circumstances with relative humidity 65% at temperature 20 °C, and is lower than that of untreated control under the same circumstances. Low EMC of heat-treated wood can't meet the demands of fungi, which need about 20% moisture content for their lives in the timber. On the other hand, the chemical degradation of wood components occurs in the high temperature, special hemicellulose and lignin. So the food for fungi decreases. Some degradative components in heat-treated wood are toxic to fungi. All of these changes are disadvantageous for fungi and can't meet their life demands.

Environmental characteristics

Whether heat-treated wood treated in shielding gases or in oil media and at relatively low temperature or at high temperature, has the typical smoky smell. The smell can disappear in several months or more, in despite of volatilization, especially for these treated at very high temperature. Its smell will affect the use more or less.

Color changes occur when timber is treated at high temperature. The surface of heat-treated wood shows brown even dark brown. The late wood shows darker than early wood after treatment. The changes of color might cause the loss of interests for the users who love the nature colors of wood.

The heat conductivity of heat-treated wood decreases by 10%-30%. Heat-treated wood in the color has better feeling than untreated control when contacted by skin.

Although some heat-treated woods are declared nature characteristics and have no bad effects on environment, the severe chemical reactions happened in treated timbers bring people more worries about the safety of the heat-treated wood. The toxicities of heat-treated wood is concerned by wood scientists and users. Kamdem, D.P. *et al.* (2000) investigated the toxicities of heat-treated wood, which underwent a relatively mild heat treatment. The researches on extractives extracted with organic solvents from heat-treated wood showed that the presence of potentially toxic compounds was produced by the heat treatment. The extractive was examined by GC-Mass spectrometry as well as by 13C nuclear magnetic resonance (NMR) to determine which type of loose chemical compound was produced by the heat treatment. The formation of some toxic polynuclear aromatic hydrocarbons derivatives of phenantrene as well as other classes of polyaromatics compounds was detected. The extent of toxic and non-toxic compounds in the heat-treated wood is not quan-

tified, but it can be stated that their proportion appears to be quite small. The lack of quantification of the concentration of these products does not ascertain if the final product is toxic or not. Nonetheless, the amount of polynuclear aromatic hydrocarbon-type derivatives should be quantified and related to the type of heat treatment process undertaken before assigning to this type of wood treatment a completely clean health safety label.

Usage of heat-treated wood

Heat-treated wood is one of important parts in forest industrial products for its special virtues. The improved properties of heat-treated wood bring a new chance into wood industry. Compared to untreated control, the most important property of heat-treated wood is low EMC which causes the excellent dimension stability and durability. Heat treatment improves the wood properties to get new usage. Nowadays heat-treated wood is mainly used in claddings, pergolas, exterior joinery, garden furniture, decks, noise barriers, etc..

Certainly, the utilizing place of heat-treated wood is slightly different according to process methods and species. In Europe market, treated pine and spruce are mainly used for exterior materials, such as garden furniture, door, window and wall, etc.. Treated birch and poplar can be used in the interior due to the dimension stability and beautiful appearance. Normally the treated temperature for heat-treated wood used in the interior is under 200 °C. Treated birch and poplar are mainly used for home furniture, kitchen furniture, decoration material for bathroom paneling and parquetry, etc.. According to different treating temperatures, heat-treated wood was recommended to be used in different scopes (Tuula *et al.* 2000). When treating temperature is between 180 °C and 210 °C, the treated wood can be used in the conditions where wood is required to have normal strength properties. The treated wood is recommended for furniture, flooring, load-bearing structures, sauna benches and other joinery products. The resistance to rot is slightly improved; If treating temperature is over 210 °C but less than 230 °C, the treated wood is recommended to be used as the products, such as yard fixtures, yard and park construction, windows and doors, jetties and carpentry products. The resistance to rot and dimension stability is much better than that of untreated wood. The bending strength and tensile strength are weaker; When treating temperature is over 230 °C, the treated wood is recommended to be used in conditions where the wood is exposed to weather or frequent wetting, but not in contact with the ground. Resistance and dimension stability are very good, but strength properties and workability are weakened. The treated wood is recommended for some special outdoor structures like wall elements.

In short, the tendency of development in heat-treated wood is transforming from previous researches to industrialization. Many new plants have been constructed or being under construction in Europe. With the further researches, better and better heat-treated wood products can be developed to meet various usages in our lives.

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